Concept, realization and characterization of serially powered pixel modules

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Abstract

We prove and demonstrate here for the example of the large scale pixel detector of ATLAS that *Serial Powering* of pixel modules is a viable alternative and that has been devised and implemented for ATLAS pixel modules using dedicated on-chip voltage regulators and modified flex hybrids circuits. The equivalent of a pixel ladder consisting of six serially powered pixel modules with about 0.3 Mpixels has been built and the performance with respect to noise and threshold stability and operation failures has been studied. We believe that *Serial Powering* in general will be necessary for future large scale tracking detectors.

I. Introduction

Modern particle detectors require on the one hand a large solid angle coverage and high granularity, on the other hand fast read-out and low power consumption. Especially particle trackers require in addition a minimum of passive material inside their active region. The high granularity results in building a detector from a large number of identical active modules. The usual power scheme is the individual, parallel powering of the modules with a constant voltage. However, this is disadvantageous for a large scale detector such as a pixel detector.

The pixel detector as the innermost sub-detector of many large scale particle detectors has a very high granularity. The ATLAS pixel detector comprises 1744 active pixel modules containing about 80 million output channels [2]. It makes use of deep sub-micron (0,25 μm) chip technology for the read-out which is necessary to achieve a radiation tolerant, compact, and high granularity detector design. Each hybrid module is composed of a 250 μm thick silicon sensor and 16 Front-End chips with a total of approx. 46 000 pixels with a size of $400 \times 50\,\mu$m.

In order to achieve a fast operation of the detector, the electronic circuits must be powered with high currents (approx. 2 A) at low voltages (1.6 V analog, 2.0 V digital). Therefore a high power density of the detector comes with the high granularity. Since the power supplies are located outside the active detector volume, the power is transmitted over a long distance (which can easily attain 100 m) and the voltages are regulated remotely from outside the active volume of the detector (for a large scale detector the distance can be larger than 10 m). Further, the power cable diameter is small inside the detector volume (typically 300 μm diameter Al wires). Together with the low voltages and high currents the power losses in the cables exceed the actual power consumption of the modules. Moreover, the further the granularity increases, the more cables are needed. This results not only in an increase of the power losses, but also increases the passive material in the active detector volume. Hence, from a certain granularity onwards the parallel powering concept is not feasible and it will become necessary to change the powering scheme.

For the *Serial Powering* concept [1] a chain of modules is powered in series by a constant current. Only two power lines per chain are needed. The voltages are generated by shunt and linear regulators implemented on the chip itself. *Serial Powering* offers a drastic reduction of power lines and therefore a reduction in passive materials in the active detector region as well as a reduction of power losses in the cables. A positive side effect is the reduction of the heat from the power lines that can uncontrollably heat up other detector systems.

In this paper we demonstrate for the ATLAS Pixel Detector that *Serial Powering* is a viable alternative for a possible upgrade of the ATLAS Inner Detector and that all the possible problems listed in the next section, concerning stability and reliability, can be solved if a dedicated *Serial Powering* design is used.

II. Example calculation on the ATLAS pixel detector

In the current powering scheme every module is connected to 8 power cables, i.e. two power lines and two sense lines for every voltage. The total voltage drop from the power supplies in the control room to the module is 6.4 V and the power losses in the cables are 191 W maximum. This is 281% of the power consumption of the 13 modules. The total lengths of all cables in the active region are 121 m, this corresponds to a radiation length of $0.073\,\% X_0$.

Since the modules of the pixel detector are organized in 114 pixel ladders (staves) with 13 modules, this suggests that the 13 modules of such a stave form a chain of serially

Table 1: Comparison between *Parallel* (using numbers from [3]) and *Serial Powering*, the power consumption is given for a ladder of 13 modules. The different *Serial Powering* schemes differ in the voltage that drops across a module.

	Parallel	Serial	Factor
Power supplies	13	1	13
No. of power lines	104	2	52
Total cable length (mm)	121160	2780	43.6
radiation length per layer x/X_0	0.073 %	0.011 %	6.5
Cable power losses	191 W	19.2 W	9.97
Module (Shuntreg. 2.0 V)	67.9 W	78 W	0.87
Module (Shuntreg. 2.7 V)		105.3 W	0.65
Sum (Shuntreg. 2.0 V)	259 W	97.2 W	2.67
Sum (Shuntreg. 2.7 V)		124.5 W	2.08

powered modules. The advantages of a serially powered chain of 13 modules follow from an example calculation (table 1):

- Passive material, i.e. power cables in the detector is reduced by a factor of 50 compared to the Parallel Powering scheme. This corresponds to 15% of the radiation length of the parallel scheme.

- Power losses in the cables are reduced by a factor 10.

- Reduced power losses in the cables also reduce heat-pick up by other detector systems.

- Voltage regulation is done on-chip, i.e. close to the consumer. The regulation can respond faster to voltage changes due to varying power consumptions.

Apparently also several concerns about *Serial Powering* arise. The first concern that the local power consumption of the module is higher than for parallel powered modules can be rejected partially from a separate calculation which includes the total heat load for the cooling system. The heat load from the cables[1] that are closest to the module is transferred to the modules and the decrease of the heat load due to less cables counterbalances the increase of the module heat. The heat that must be cooled by the cooling system decreases by 7% (*Serial Powering* scheme with 2.0 V voltage drop across a module) or increases maximally by 17% (scheme with 2.7 V voltage drop across a module). Additionally, the heat is now produced close to the cooling and as mentioned above there is less heat pickup by other detector systems, so that the slight increase of the heat load has overall positive effects on the detector.

The fear of loss of a whole chain due to one defect regulator is addressed by the *Serial Powering* scheme (see III). The major concern of noise pickup of the chain by noise sources or noisy modules is rejected by the measurements in B.

[1]The heat load per cable is approx. 2 W.

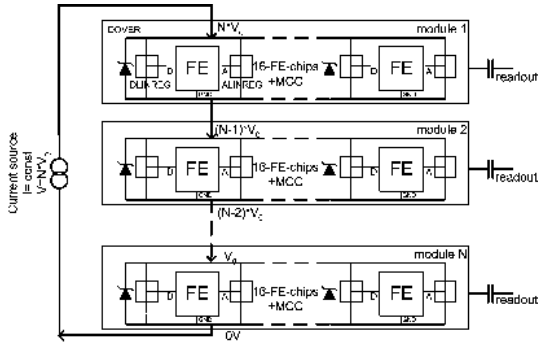


Figure 1: A chain of serially powered modules, each built according to the *Extended Serial Powering* scheme

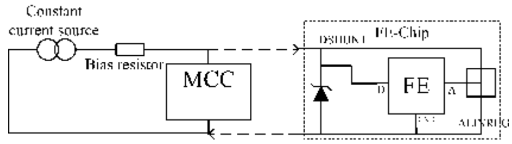
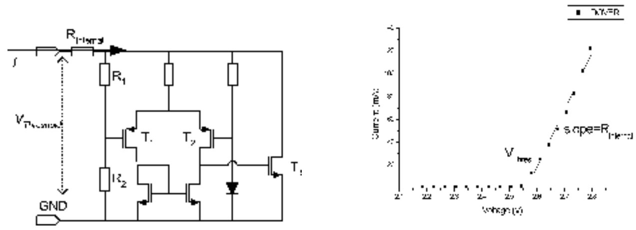


Figure 2: Schematic of the *Simple Serial Powering* scheme using only one linear regulator



(a) Schematic of a shunt regulator

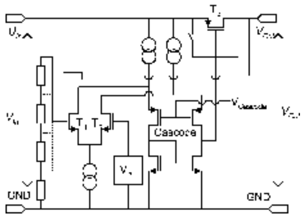
(b) Current/voltage characteristic curve of the regulator which is similar to a Zener diode

Figure 3: Shunt regulator as it is implemented three times on the FE-chips with two characteristic values: threshold voltage and internal resistance (slope)

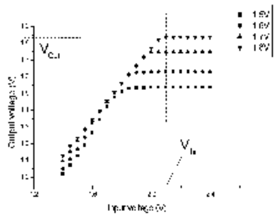
III. General Serial Powering Scheme

Figure 1 shows a chain of serially powered modules (*Extended Serial Powering* scheme [1]). A constant current source is connected to the power input of the first module. The ground of the module is then connected to the power input of the next module etc. The current consumption is determined by the highest current consumption of one module in the chain. The supply voltages of the chips are generated by two types of regulators. One is a shunt regulator which behaves like a Zener diode. The other one is a linear voltage regulator that generates a constant output voltage from an arbitrary and higher input voltage.

On the chip there are three shunt regulators, DSHUNT, AOVER and DOVER that have design threshold voltages of 2.0 V, 2.4 V, and 2.7 V, respectively. The two linear regulators ALinReg and DLinReg have adjustable output voltages in four steps from 1.5 V to 1.8 V or 1.8 V to 2.4 V, resp. Figure 3(a) shows the schematic of the used shunt



(a) Schematics of the linear regulator



(b) Output characteristic curves for four settings of the output voltage

Figure 4: Linear regulator as it is implemented twice in the FE-chips to power the digital and analog part of the chip, respectively.

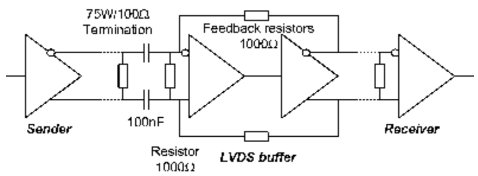


Figure 5: AC-coupling scheme, used to read out modules that have different ground potentials compared to the read-out electronics

regulator. A typical output characteristic curve is displayed in figure 3(b). Figure 4(a) shows the schematics of the linear regulators. Figure 4(b) shows a typical output characteristic curve for a linear regulator with four different output voltages.

On a module the shunt regulators of all 16 chips are connected in parallel. This stabilizes the output voltage. The fear of a loss of a whole module chain is also addressed this way. The redundant use of the shunt regulators can maintain the voltage regulation and the chain remains uninterrupted even if one or more regulators should break. Thus the risk of loosing a whole chain is minimized. The common output voltage of the shunt regulators is the input voltage for the two linear regulators of every chip. The outputs of the regulators are already internally connected to the analog and digital part, respectively. The suitable regulators for this scheme are therefore the two linear regulators that are powered by the DOVER regulator. As the modules now have different ground potentials, the read-out must be done via AC coupling of the signals (fig. 5).

One alternative *Serial Powering* schemes can also be considered. The *Simple Serial Powering* scheme (fig. 2) uses the DSHUNT regulator to power the digital part and the analog linear regulator. In this scheme the total voltage which drops across a module is lowest (2.0 V) and therefore also the power consumption of a single module is the lowest. A disadvantage is that the digital voltage is fixed to the threshold voltage of the shunt regulator.

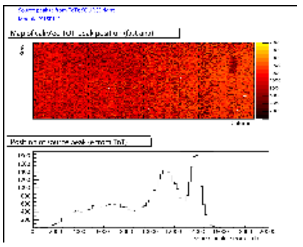
Figure 6: Picture of the measurement setup with (A) the module ladder (half-stave) with six serially powered modules containing about 0.3 Mpixels, (D) AC coupling read-out and power routing board, (E) constant current power supply, (F) pixel read-out electronics

IV. Operation of a serially powered module ladder

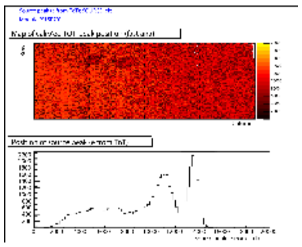
After testing and comparing single serially powered modules [1] [6], which were built with already existing ATLAS pixel chips and a dedicated flex-hybrid, six *Serial Powering* modules were composed to a ladder, a so called half-stave, containing about 0.3 MPixels. The measurement setup is shown in figure 6. The same original carbon-carbon structure for modules ladders was used except for the reduced number of modules. The serial connections between the modules was made by original type-0 cables which were connected to a special board that routes the current serially through all modules. Additionally it AC-couples the LVDS signals between the modules and the external read-out electronics through a pair of capacitors and a LVDS buffer for each data line. The operation commands could be sent to all modules at the same time. This emulates the situation in the detector when all modules are individually having digital and analog activities and varying power consumptions. As first qualitative proof of operation, figures 7(a) and 7(b) show the spectrum of a ^{241}Am point source placed above and between two modules and recorded simultaneously. The left hit map corresponds to the module that was on the left side of the source etc. In the spectrum two peaks can be seen. The peak at higher deposited charge is due to the absorbed 59.54 keV-photon. This tests the whole detection chain from the charge collection in the sensor, the hit processing in the chip and the output of the hit data. It is a qualitative proof of the full module functionality.

A. Performance Characterization

The performance of each module while serially powered with five other actively working modules was measured. The measurements were repeated until all six modules were read out. Figure 8 shows the threshold maps



(a) Spectrum of a ^{241}Am source placed right to the module



(b) Spectrum of a ^{241}Am source placed left to the module

Figure 7: Spectrum of a ^{241}Am source placed between two modules and recorded simultaneously

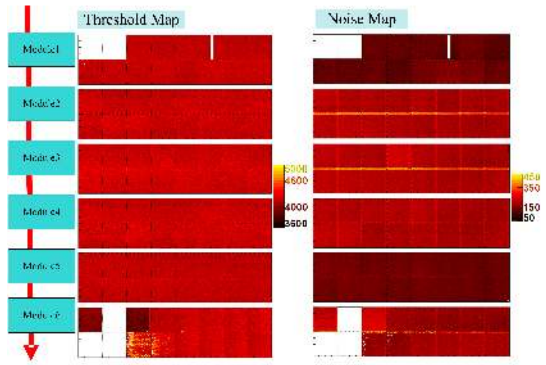


Figure 8: Thresholds and noise maps of the six serially powered modules (some modules without sensor or with defect chips) on the module ladder (half-stave)

Table 2: Threshold, threshold dispersion and noise of six serially powered modules on a module ladder (noise difference to singly serially powered). Except for module 6 all modules were built according to the *Extended Serial Powering scheme*.

Module	thresh. (e^-)	disp. (e^-)	noise (e^-)
M1	4134	57	127^+ (4)
M2	4156	69	182 (-1)
M3	4173	70	186 (-0)
M4	4162	70	183 (-4)
M5	4132	58	133^+ (0)
M6	4160	91	172 (-5)
Parallel	4062	50	160

$^+$ w/o sensor

and the noise maps of the six modules[2] and table 2 shows the threshold, threshold dispersion and noise performance of the six modules. This is the first time that such a large chain of serially powered modules was powered and that all modules were operated at the same time. The results in comparison to singly serially powered operation (i.e. only one module is serially powered and active) and parallel powered modules show hardly any influence of the modules on each other during normal operations.

[2]Some modules are without sensor or with some defect chips because of cost reasons, still the vast amount of pixels can give a good impression of the module's performance.

Table 3: Noise difference of the modules on the module ladder between normal operation and operation with one noisy module in the chain. Each row is a different measurement with a different noise module. Except for module 6 all modules were built according to the *Extended Serial Powering scheme*.

Noisy module	M1 (e^-)	M2 (e^-)	M3 (e^-)	M4 (e^-)	M5 (e^-)	M6 (e^-)
M1	—	13	2	2	13	3
M2	6	—	10	5	0	9
M3	0	2	—	2	0	3
M4	1	9	2	—	0	9
M5	10	2	1	15	—	20
M6	0	2	2	2	0	—

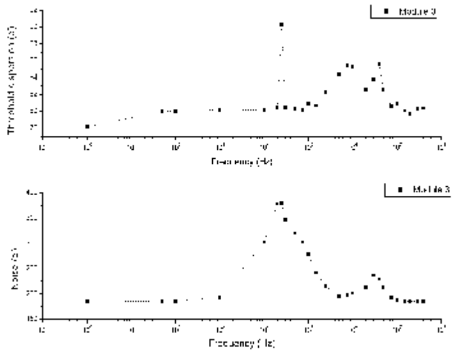
B. *Failure Mode Studies*

Two types of failures are studied in order to test the reliability of the *Serial Powering* scheme. The first was the study of the effect of a noisy module in the chain. This was achieved by lowering the detection threshold of one module to almost zero, so that this module sees noise hits all the time. That involves a permanent analog and digital activity as well as permanent changing current consumptions which can stress the powering of the other modules by permanently changing the potentials across the modules. The measurement was repeated six times, so that each time a different module was made noisy and the effect on the other modules was investigated. Table 3 shows the noise difference of every module between the failure mode measurement and the normal operation. Each row is a different measurement with a different noisy module.

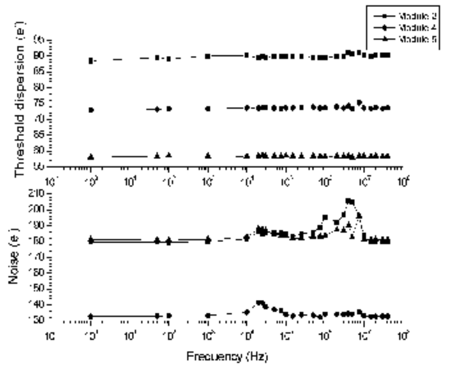
The increase in noise for neighboring modules in the chain is small (max. 20 e$^-$) compared to the normal noise of 170 e$^-$ to 200 e$^-$ and it is well below the ATLAS requirement for the maximum noise. This shows that the filtering and the regulation of the supply voltages is sufficient enough to filter such a disturbance on the power lines.

The second type of failure mode tested is a noisy module emulated by an external switchable load connected in parallel to one module. The distortion was tuned to different frequencies up to 40 MHz. The load varied between 300 mA and 500 mA. This constitutes a much more massive interference to the supply current than a noisy module. The effect on the chain is again a shift in potentials for all modules.

Figure 9(a) shows the frequency dependence of the threshold dispersion and the noise of module 3 which was parallel to the switchable load. During the whole measurement module 3 could be configured and read out sequentially without any problems. Only the noise rises in two regions around 25 kHz and around 3 MHz to undesired values of 350 e$^-$ resp. 230 e$^-$. More important is to observe the effect on the other modules and if the neighboring modules pick up the higher noise from module 3. Fig-



(a) Frequency dependence of the threshold dispersion and the noise of the module that was parallel to the switchable load



(b) Frequency dependence of the threshold dispersion and the noise of the modules neighboring the module that was parallel to the load

Figure 9: Dependence of the threshold dispersion and the noise of the modules in the chain on the frequency of the switchable load

ure 9(b) shows the frequency dependence of the threshold dispersion and the noise of the three neighboring modules in the chain. Clearly the change in noise and threshold dispersion is small for all modules[3]. Therefore there is hardly any noise pick up by *Serial Powering* modules from noise on the power line. We consider this experimental test a very important demonstration that the *Serial Powering* scheme is reliable.

V. Summary

We have demonstrated that *Serial Powering* is a viable concept to provide operation power to a large pixel detector system such as the ATLAS pixel detector at LHC. A powering scheme that powers a chain of modules with a constant current and uses dedicated on-chip voltage regulators and modified flex hybrid circuits has been devised and implemented for ATLAS pixel modules.

An example calculation shows that such a chain of 13 modules offers a reduction in power losses of the cables by 90% and a reduction in passive materials by 98%, this is a reduction of 85% in radiation length. It has been shown that the spread in quality of the voltage regulators, as the key elements to this powering scheme, is sufficiently small and the voltage stability of the linear regulators is excellent, so that the voltage regulators are applicable for Serial Powering. The serially powered modules have been intensively tested in the lab and in test beams. The comparison between parallelly powered and serially powered modules has shown no difference between the two powering schemes. Finally, the equivalent of a pixel ladder consisting of six serially powered pixel modules with about 0.3 Mpixels has been built and the performance with respect to operation failures has been studied. Measurements with artificially noisy modules mimicked by inducing noise on the power lines have only shown a marginal increase in noise of the other modules in the chain. All major concerns about *Serial Powering* are therefore unfounded. We strongly believe that Serial Powering is not only a viable powering scheme for an upcoming upgrade of the ATLAS pixel detector, but is also viable, if not absolutely necessary for future large scale tracking detectors.

[3]module 5 is again without sensor

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